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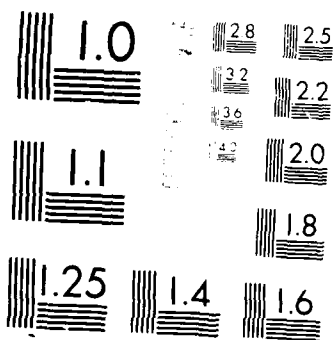
THE PROPERTIES OF SOUND PROPAGATION IN LIQUID
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The Properties of Sound Propagation in Liquid Constrained Viscoelastic and Polymeric Structures

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Laboratory for Computational Physics and Fluid Dynamics

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) Detailed experiments were conducted to study the sound propagation in liquids contained by pipes constructed of polymeric materials. In the experiments, vertically aligned cylinders containing water were ensounded at one end by a piston-driven sound source. Approximately 60 dB sound attenuation was observed in pipes constructed of viscoelastic materials, the effect increasing with frequency and loss-tangent. Sound propagation in more rigid polymeric pipes exhibited similar characteristics to that of metallic pipes, in that negligible attenuation was observed.					
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THE PROPERTIES OF SOUND PROPAGATION IN LIQUID CONSTRAINED VISCOELASTIC AND POLYMERIC STRUCTURES

INTRODUCTION

A considerable amount of theoretical and experimental work has been done in the past on propagating wave phenomena within elastic tubes containing fluids. Concentration has centered about the effects of wall elasticity on the propagation of sound waves through compressible media such as air and nearly incompressible liquids such as water (1-5). These studies can be segregated into low-frequency propagation, where the pressure is essentially planar across a wave front and high-frequency propagation, where axisymmetric modes dominate. Of practical interest is that general class of studies concerning both types of wave propagation in flexible tubes with viscoelastic properties (6-7). Relatively little data has been presented in the literature for these cases.

The present investigation attempts to remedy this lack of data by means of presenting a detailed experimental study of sound propagation within liquids contained by polymeric materials with a range of viscoelastic properties. Densities and bulk wave propagation velocities associated with the solid and liquid media are comparable in magnitude. Sound Pressure Level (*SPL*) is reported as a function of axial position in the liquid column, frequency and pipe wall material. The results indicate the degree of attenuation of propagating sound that can be realized by an appropriate choice of duct wall composition. The *SPL* is also examined in one pipe wall construction (acrylic) to establish the parametric ranges over which the propagating wave in the pipe is not only axisymmetric but also nearly planar. The extent to which energy input may affect the characteristics of the moving piston used to ensonify the liquid column is also examined.

EXPERIMENTAL APPARATUS and PROCEDURE

The experimental set-up shown in Fig. 1 consisted of a piston-driven sound source, a rigid test stand and a 1.829 m long pipe section with rigid flanges at both ends. The fluid column (water) was continuously excited by the sound source after which the sound pressure level was obtained from an omni-directional hydrophone located on the pipe centerline. Care was taken to mechanically isolate the sound source from the pipe segment in order to prevent direct excitation of the pipe walls. Detailed measurements of sound

pressure level were made as a function of frequency, location in the liquid column and pipe wall material over a total bandwidth of one kHz . One pipe section (acrylic) was instrumented with flush-mounted pressure sensors on the interior wall (located 1.372 m above the sound source) which, together with the omni-directional hydrophone located at various radial locations, provided a means of determining the frequency range over which the propagating wave in the pipe was nearly planar. Accelerometers were mounted both on the pipe wall and the test stand to determine structural vibration modes and their interaction with the fluid column.

As indicated in Fig. 1, two methods of obtaining the data were available. The sound source could be driven with a random noise generator and the spectrum analyzer used to obtain pressure spectra. Virtually identical results were obtained with the alternative technique of using the sweep oscillator and tracking filter. However, the latter method was utilized in the experiments reported here because it provided more precise resolution in frequency over the bandwidth investigated. Table I presents the physical properties of the pipe wall materials investigated and Table II summarizes the type and specifications of the relevant instrumentation and hydrophones used.

Table I -- Pipe Material Characteristics

type	Wall	ID	Density	Elastic	Loss
	Thickness			Modulus	Tangent
	(cm)	(cm)	(gm/cc)	(GPa)	
Steel	0.953	20.32	7.8	200.0	0.001
Acrylic	0.635	19.05	1.18	2.4	.08
PVC	1.365	19.05	1.38	2.8	.08
Rubber*	2.540	19.05	0.93	.20-.35	.12-.15
Hypalon*	2.540	19.05	1.1-1.3	.08-.31	.16-.95

* Silicone-lined

Table II -- Instrumentation

1.	Spectrum Analyzer	-----	Nicolet Scientific Corporation		
			Model 0-400, Range: 0 to 100kHz		
2.	Random Noise Generator	-	General Radio Co., Type 1390-A,		
			Range: 0 to 5 MHz		
3.	XY-Plotter	-----	Hewlett Packard, No. 136A		
4.	Ithaca Amplifier	-----	Model 252-AM, Range:-20 to 60 dB		
5.	Power Amplifier	-----	Ling Electronics, Model TD-450		
6.	Tracking Filter	-----	Spectral Dynamics Corp.		
			Model SD 131L		
7.	Sweep Oscillator	-----	Spectral Dynamics Corp.		
			Model SD 104A, Range: 5 to 5 KHz		
8.	Sound Sources		Size		Range
		-----	-----		-----
	J9 - USRD		5.7 cm		40 Hz - 20 KHz
	J11 - USRD		10.0 cm		20 Hz - 12 KHz
9.	Hydrophones		Sensitivity (ref 1 volt/upa)		Diameter
		-----	-----		-----
	Omni-directional		-210.0 dB		2.54 cm
	Flush-mounted		-202.0 dB		0.23 cm

The steel, acrylic, and PVC pipes consisted of single 1.829 m long sections at the diameters indicated. The rubber and hypalon sections (manufactured by General Rubber Company) were fiber-reinforced pipes obtained in 60.96 cm long, 20.32 cm diameter sections. Each section was lined with a 0.635 cm thick silicone rubber sleeve to give them the same inside diameter as the acrylic and PVC sections. Three sections each of these two materials were joined to give a single pipe of equivalent length to those made of acrylic and PVC.

In order to assess the possible influence on the experimental results by the size of the moving piston used to drive the liquid column, characterization of the *SPL* in two pipe materials was conducted both with the large and small sound sources (piston diameters of 10.00 cm and 5.70 cm respectively). The pressure spectrum was obtained at 5.08 cm above the sound source and every 30.48 cm thereafter along the pipe centerline. Both sound sources were driven at the same input power level in experiments with the second and fourth pipe materials listed in Table I. In addition, the large sound source was driven at full and half power for the acrylic pipe to establish that the input power level was proportional to the measured acoustic levels over the frequency range studied.

The *SPL* on the centerline of all five pipe materials were compared at a fixed axial position relative to the large sound source as a measure of the sound attenuation in the liquid column which may be realized by an appropriate choice of duct wall material.

INITIAL CONDITIONS and ENERGY INPUT

The effects of the size of the piston face on the resultant pressure spectrum are shown in Figs. 2 and 3 for acrylic and rubber pipe segments respectively, where the ratios of the *SPL* at 91.44 cm to that at 5.08 cm (along the pipe centerline) are plotted. In these, and subsequent figures, P_i^* is the normalized pressure ratio P_c/P_o where P_c is the centerline pressure at a specific axial location and P_o is the centerline pressure at 5.08 cm. The results for the large and small sound sources in each pipe are qualitatively similar. Resonant peaks occur at identical frequencies with both sound sources. The amplitudes of these peaks are greater for the large sound source than for the smaller one (as much as 5 dB for the acrylic pipe). This amplitude difference is readily explained. The acoustic energy propagating away from the source will be nearly constant over that portion of the pipe cross-sectional area adjacent to the piston face and zero over the remainder of the pipe diameter. The hydrophone measurement made at 5.08 cm from the source is influenced only by that portion of the distribution over the sound source. As the wave propagates along the pipe, the energy becomes more uniformly distributed over the pipe cross-section. The ratios of the *SPL* shown in Figs. 2 and 3 have lower peak amplitudes for the smaller sound source due to the normalizing pressure being larger relative to the average value over the whole pipe cross-section where the piston is located. In quantitative terms, the average pressure, P_{avg} , can be expressed simply as,

$$P_{avg} = \frac{1}{A_p} \oint P dA. \quad (1)$$

where A is the pipe cross-sectional area, A_p is the piston area and P is the effective pressure (as a function of radius) generated at the piston face. If the sound pressure level is assumed to have a constant amplitude P_0 over the face of both moving pistons and zero elsewhere in the pipe cross-section, then for circular areas Eq. (1) can be used to form the following ratio.

$$\frac{P_{i \text{ large}}^*}{P_{i \text{ small}}^*} = \frac{A_{\text{large}}}{A_{\text{small}}} \quad (2)$$

For the two sound sources listed in Table II, the peak log ratios shown in Figs. 2 and 3 would increase by approximately 5 dB more for the large sound source than for the smaller one. As indicated, the differences in peak values with the two sound sources are in satisfactory agreement with this simplified analysis. Note that Fig. 3 indicates a smaller difference between sound source amplitudes, but as explained later in this report, this is a result of the viscoelastic properties of the rubber material used.

On a similar note, results obtained with the large sound source established the linear relationship between input acoustic power and recorded acoustic levels at various locations in the liquid column. When comparing pressure ratios, no variation was found to exist between results obtained when driving the large sound source at full or half power in any of the five pipe materials used.

RADIAL PRESSURE DISTRIBUTION

The pressure spectrum was measured at various radial positions at 1.372 m above the large sound source. These results, along with that of a flush mounted sensor located on the interior wall of the acrylic pipe, are compared in Fig. 4. Two points of interest are noted. First, the zeroth order axisymmetric mode is seen to be nearly planar up to approximately 300 Hz by observing the omni-directional hydrophone output ($r/r_p = 0.5, 0.75$). Thereafter, the wavelength of the propagating wave approaches the pipe diameter, and the radial distribution begins to be frequency dependent.

The experimentally observed radial pressure distribution compares favorably with that which is anticipated from the analytical work by Junger (3). For the case where the ratio,

$$\left(\frac{C_a}{C}\right)^2 \ll 1, \quad (3)$$

which is characteristic of the present experimental work.

$$\frac{P}{P_c} = I_0 \frac{\omega r}{C_a} \quad (4)$$

Here C_a is the propagation velocity of an axisymmetric pressure wave in the pipe fluid and C_c represents the propagation velocity of a plane acoustic wave in an infinite domain of the liquid. P and P_c denote the pressures at radius r and on the pipe centerline respectively, and ω denotes frequency in rad/sec. The relationship of C_a to C_{a0} (C_{a0} being the quantity corresponding to C_a in the low frequency limit) takes the following form in these circumstances:

$$\frac{C_a}{C_{a0}} = \frac{1 - \nu^2 + (x^4/12)(h/a)^2}{(1 - \nu^2)(x^2/2) \left[\left(\frac{\rho}{\rho_i} \right) \left(\frac{h}{a} \right) + \frac{I_0(x)}{x I_1(x)} \right]} \quad (5)$$

Here ν , h and a denote Poisson's ratio, tube wall thickness and radius respectively, while ρ and ρ_i are the densities of the tube wall and the interior liquid. $I_0(x)$ and $I_1(x)$ represent modified Bessel functions of the first kind (of order 0 and 1 respectively) and x equals $\omega a/C_a$. The solid lines in Fig. 4 are representative of Eqs. (4) and (5).

The flush mounted sensor output (at $r/r_p = 1$) deviates somewhat from that predicted by the theoretical analysis. In particular, the increase in the ratio P/P_c is frequency dependent over the 0 to 300 Hz range. Above 300 Hz, the experimentally measured pressure ratio increases with frequency at about the same rate as the theoretically predicted result. In this higher frequency range, the difference in the absolute value of the experimentally measured and theoretically predicted results differs by slightly more than 3 dB; about the same as the difference at 300 Hz. Although great care was taken to isolate these sensors from vibratory effects, no amount of damping could eliminate this low frequency contamination. The lower elastic modulus of acrylic material as compared to steel amplified the radial vibration modes at the wall and indeed the accelerometer data obtained at the wall sensor location confirmed this effect.

The second point of interest is reflected by the approximate 2-7 dB increase in pressure at higher frequencies as demonstrated by the results at 1000 Hz. Acrylic pipe, although less rigid than steel, has a considerably higher elastic modulus than rubber and hypalon (see Table I). It is therefore expected that even greater pressure variations would be observed in

these pipes, with the propagating axisymmetric wave being planar over a correspondingly lower frequency range.

ATTENUATION CHARACTERISTICS

Figures 5 and 6 show the more practically important results of this investigation. The *SPL* was measured along the pipe centerline at an axial distance of 91.44 cm from the sound source in pipes constructed of all five pipe materials. Table I has indicated the similar properties of the acrylic and PVC pipe segments and this is reflected by the similar magnitudes and peak frequencies in Fig. 5. However, due to the larger PVC wall thickness and its slightly larger density, the resonant peaks for PVC have uniformly shifted to slightly higher frequencies. In both cases, the resonant peaks occur at approximately.

$$f = 100(2n + 1) \text{ Hz}, \quad n = 0, 1, 2, \dots \quad (6)$$

As depicted in Fig. 5, the PVC and acrylic pipe results have a somewhat lower *SPL* at the first resonant frequency of 300 Hz for the steel pipe. This is due to the negligible loss tangent of the latter material. (It should be noted that the second apparent peak at about 700 Hz for steel is due to structural resonance only, for by adding more mass to the base of the experimental structure, this peak could be reduced without changing any of the pressure spectra.

Using the acrylic results from Fig. 5 for comparison, a considerable amount of attenuation is observed in Fig. 6 for the rubber and hypalon pipe materials. This attenuation becomes evident at the first resonant peak, reducing it in amplitude by slightly more than 10 dB. It becomes larger with increasing frequency, approaching 15 dB and more than 60 dB at 1000 Hz in the rubber and hypalon sections respectively. The shear storage Modulus G' and loss modulus G'' , were measured for the rubber and hypalon materials using a Weissenberg Rheogoniometer, Model R1S. The loss tangent was somewhat frequency dependent over the bandwidth investigated with a much larger value for hypalon at 1000 Hz (see Table I) which is explicitly represented in the results of Fig. 6. These combined results indicate the distinct advantage by which viscoelastic materials (with high loss tangent) may be used to eliminate extraneous sound within experimental and industrial facilities.

As a final note one might well ask if the pressure variation introduced by the finite diameter of the sound source (at 5.08 cm) is contributing to these large attenuation characteristics. Therefore, a similar log-ratio for acrylic and rubber is presented in Fig. 7 in which case, a measurement at 30.48 cm from the sound source was used to normalize the pressure spectra. As shown the attenuation characteristics of Fig. 6 are confirmed with the slightly smaller differences indicative of the closer spacing of the two measuring positions.

CONCLUSIONS

An experimental study of sound propagation in liquid-filled ducts has established the utility of viscoelastic wall materials for sound attenuation within piping systems. The effectiveness of such materials for attenuation purposes increases with frequency over the range of parameters considered. As verified experimentally, the most effective materials have low shear moduli and high loss tangents. Pipes made of polymeric materials such as acrylic and polyvinylchloride (PVC), which do not have these characteristics at room temperatures and over the frequency range considered, exhibit a relatively small degree of sound attenuation. Viscoelastic materials appear to offer the potential of much needed sound attenuation in experimental and industrial piping configurations where sound filters, such as large cavities or sound baffles, are flow restrictive and therefore are of no advantage. The chief disadvantage appears to be the lesser effectiveness of viscoelastic materials at very low frequencies.

ACKNOWLEDGMENT

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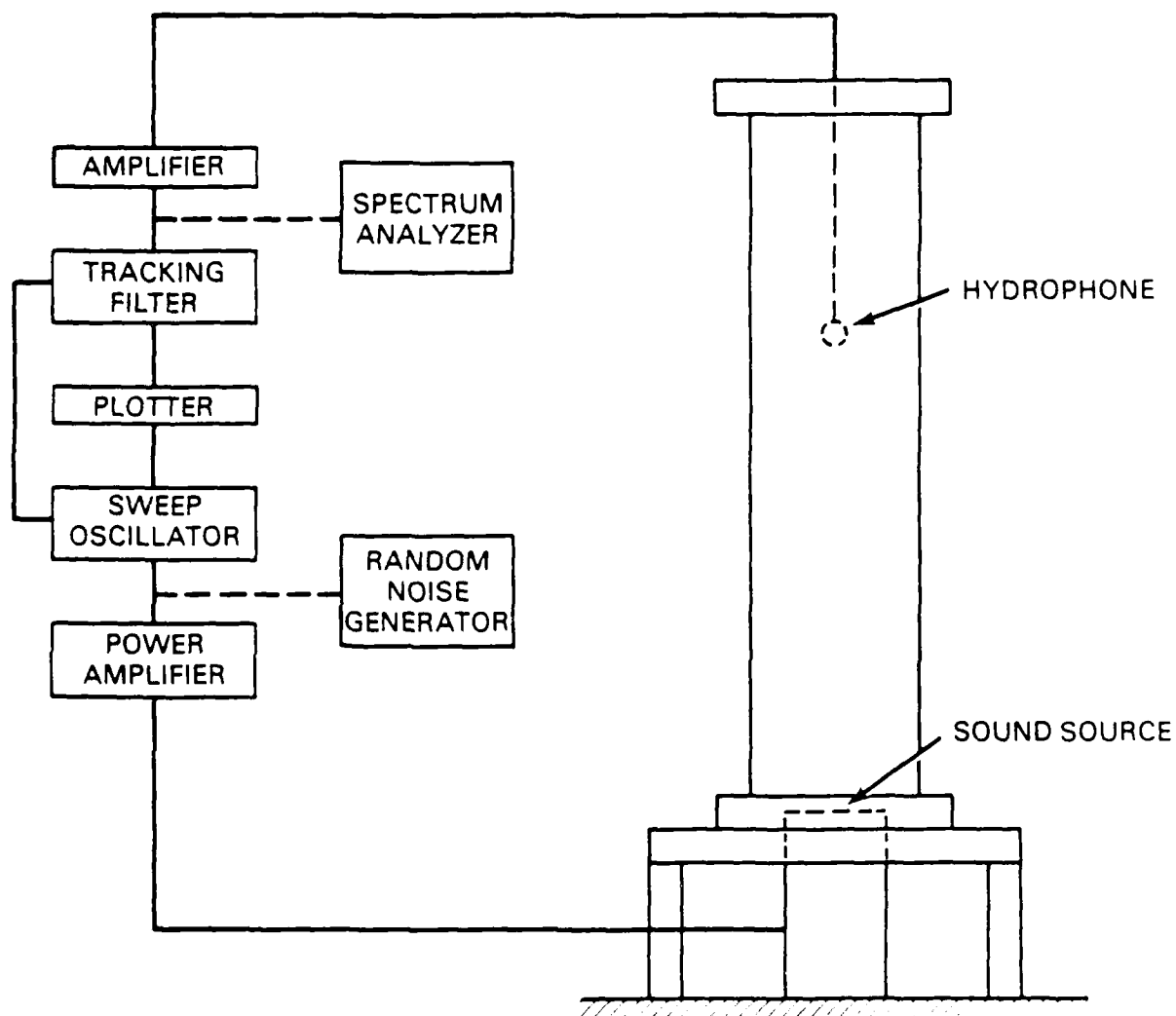


Fig. 1 — Schematic of Test Apparatus

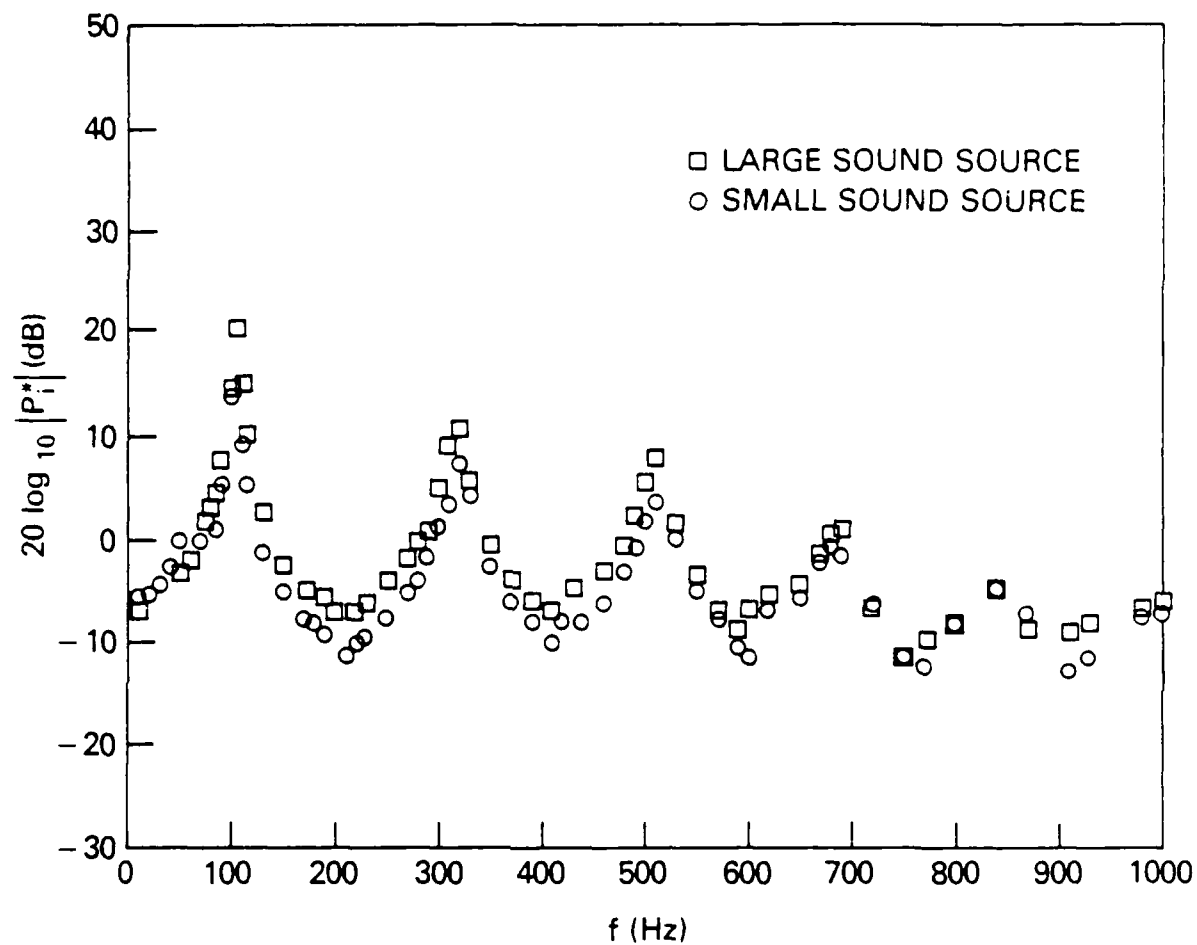


Fig. 2 — Ratio of acoustic pressure recorded at axial positions of 91.4 cm and 5.1 cm for acrylic pipe.

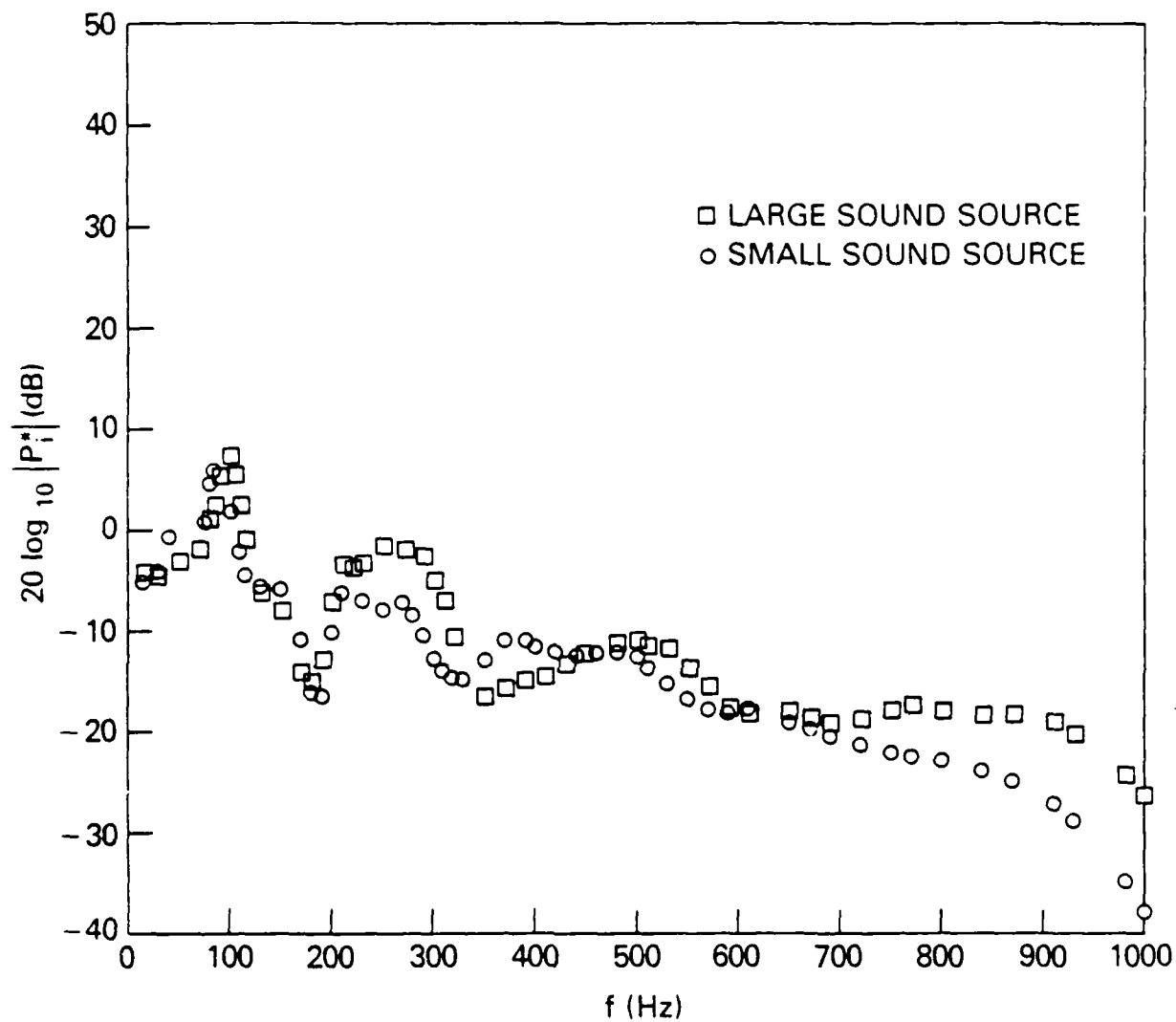


Fig. 3 — Ratio of acoustic pressure recorded at axial positions of 91.4 cm and 5.1 cm for rubber pipe.

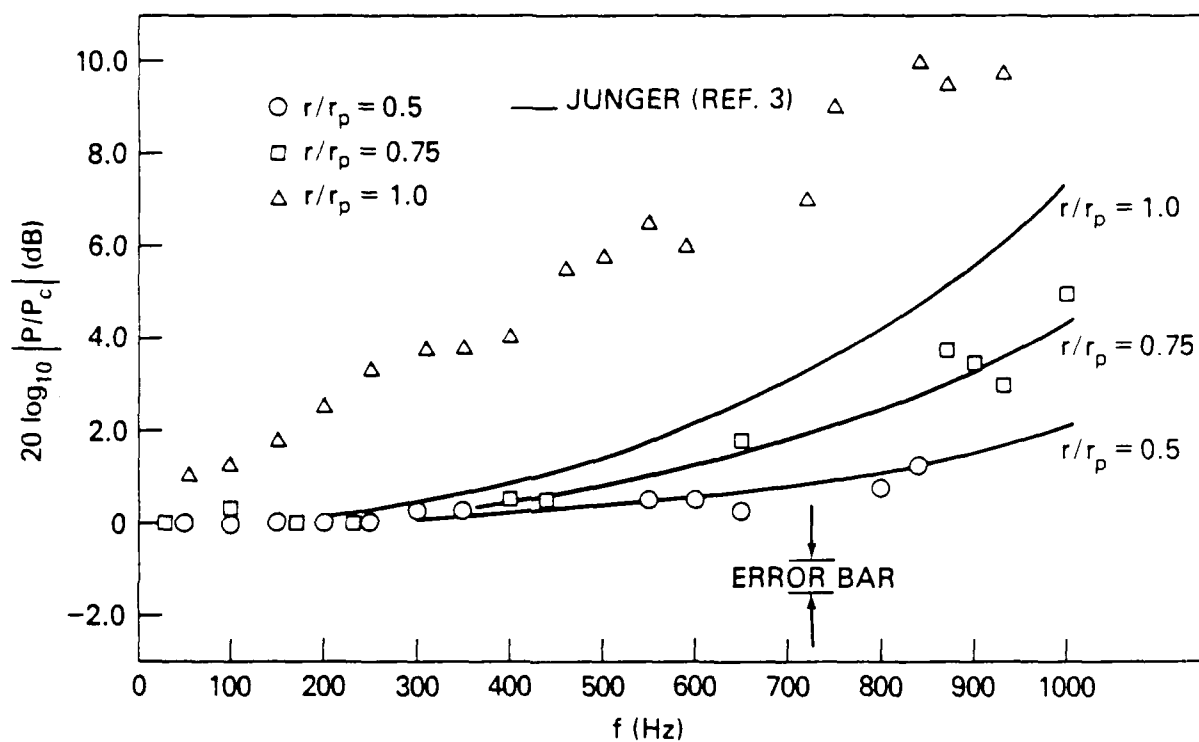


Fig. 4 — Radial variation of acoustic pressure at 1.372 m from the sound source in acrylic pipe.

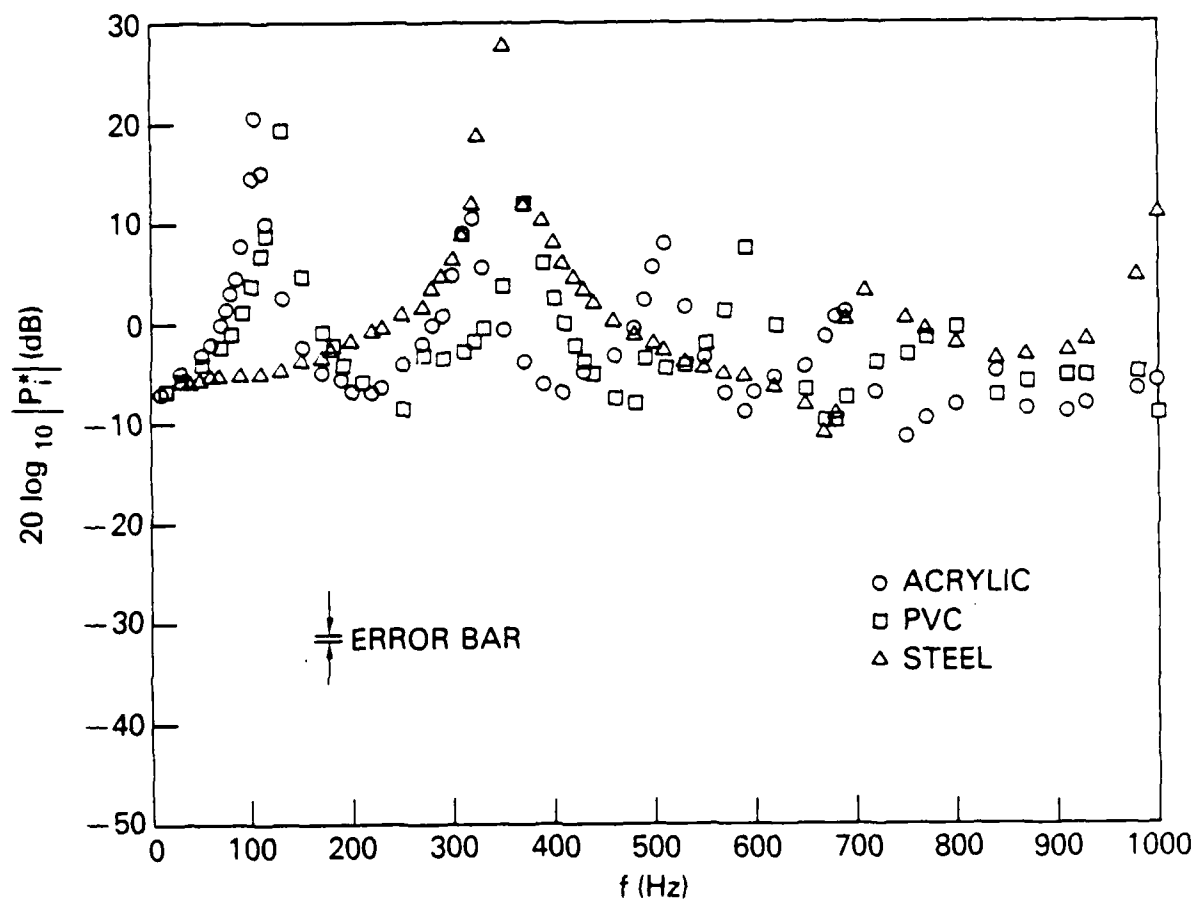


Fig. 5 — Comparison of attenuation characteristics between steel and the polymeric pipe materials at 91.44 cm.

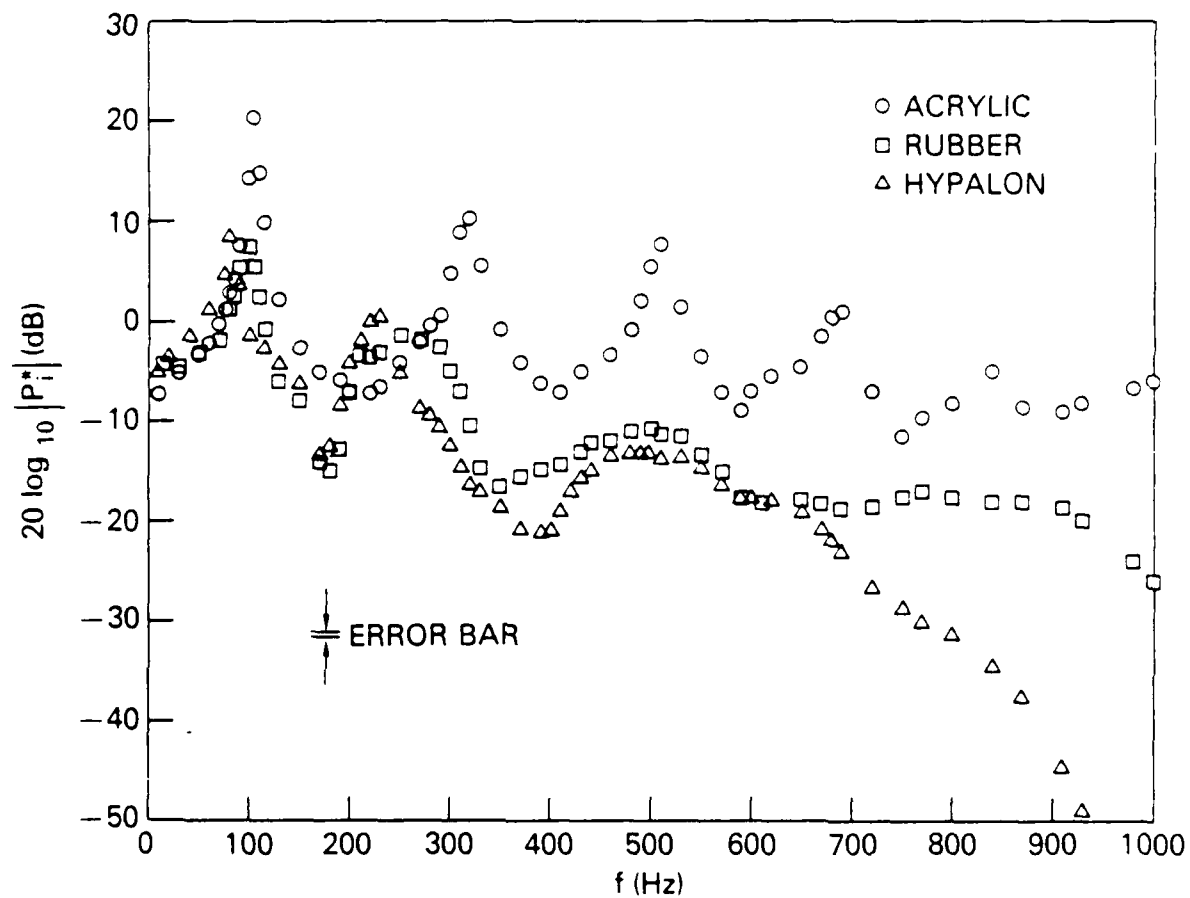


Fig. 6 — Comparison of attenuation characteristics between viscoelastic materials and the more rigid acrylic pipe at 91.44 cm.

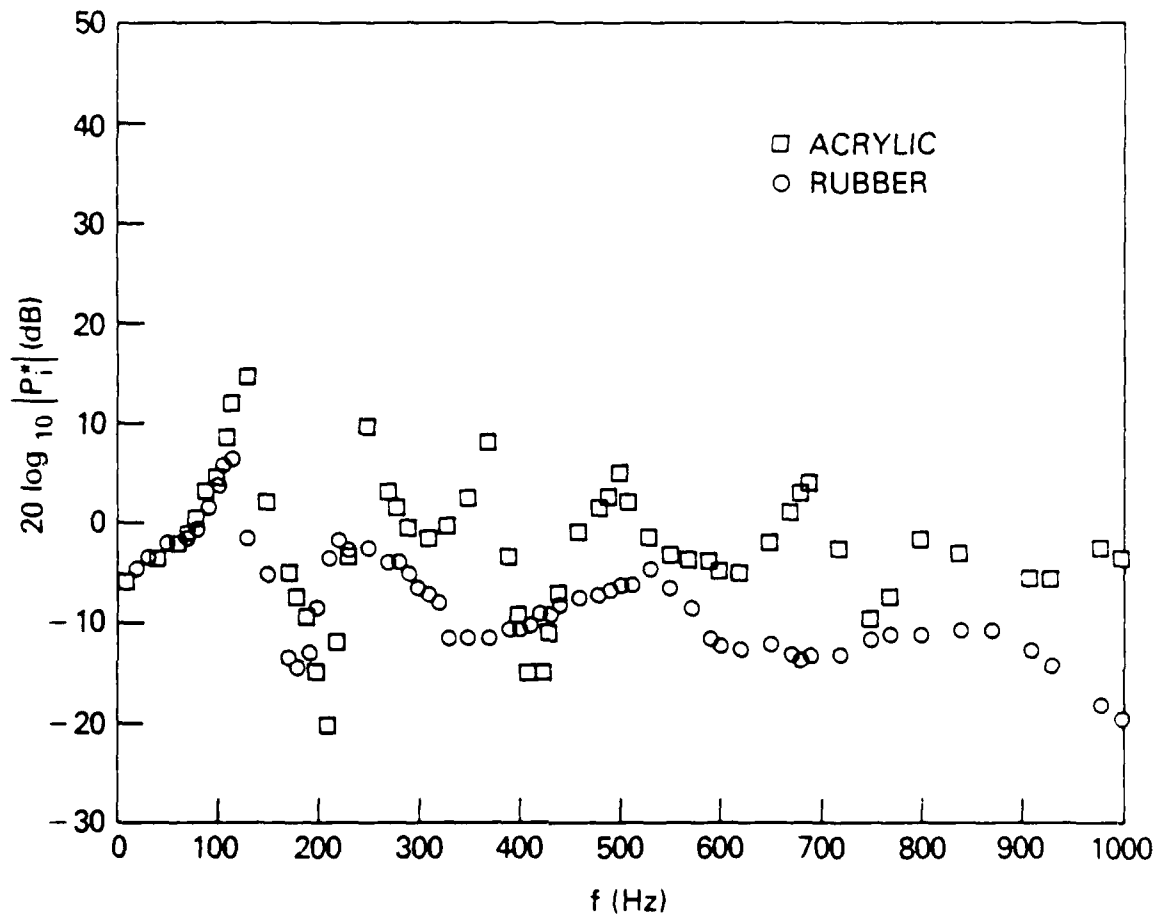


Fig. 7 — Acrylic and rubber attenuation properties at larger axial normalizing position (30.48 cm).

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